LOW ENERGY DESALINATION: SIEMENS' SOLUTION TO A GLOBAL CHALLENGE

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Abstract

It is estimated that 3 billion people will live in water stressed regions by 2025. At 97.5% of the world's water supply, the seawater represents a seemingly endless supply of water. The best available technologies, however, have not been able to efficiently and cost effectively tap this vast resource. High power consumption, complicated pretreatment processes, high cost/corrosion resistant pipes and valves, and process safety concerns contribute to an overall cost barrier to widespread employment of seawater desalination. Though improvements continue to be made, many of the currently employed technologies have been pushed near their performance and efficiency limits. There have been several recent advances to seawater desalination technology including Membrane Distillation, Forward Osmosis, and Capacitive Deionization. Siemens offers another potential solution, a hybrid process employing Electrodialysis (ED) and Continuous Electrodeionization (CEDI).

In August, 2007, the Singapore Government offered a Challenge Request-For-Proposals (RFP) to industry/institutions to seek ideas for innovative technology for producing World Health Organization (WHO) quality water from seawater at an energy consumption of 1.5 kWh/m^3 or less. Siemens was announced the sole winner of the contest in June, 2008 from 35 proposal submissions. After two years of intense research and development, Siemens is quickly approaching a low-energy, seawater desalination solution. Process and design developments from the lab bench to full size ED modules have yielded a process to produce drinking water from seawater at approximately half of the best available technology. Details of the development process, including the test results of a 50 m^3/day demonstration system operating on seawater in Singapore will be summarized. In addition to this, Siemens efforts toward commercialization will be shared.

I BACKGROUND

1.1 Market

An estimated three billion people around the world live in water-stressed regions and only one percent of the world's freshwater is readily accessible for direct human use. In contrast, seawater provides a virtually unlimited resource; 97.5% of the water on earth is saltwater. Desalination technologies, one of the major solutions for alleviating water shortages, already produces clean drinking water in 40 countries.

Most desalination capacity today is installed in the Arabian Gulf and the Mediterranean where there are acute shortages of drinking water and an abundance of financial resources. Distillation-based desalination is mainly deployed in Mideast countries because of an abundant supply of waste heat available from oil refineries. Figure 1 shows the breakdown of market share for the major desalination technologies. Reverse Osmosis (RO) is the prevalent technology in the remaining parts of the world due to its lower energy requirement for desalination compared to distillation. ED and EDR have mostly been deployed in brackish water applications, and have been considered too expensive for seawater desalination. Even with lower RO desalination costs, the cost is still considered too high for widespread adaptation when compared to conventional means of obtaining drinking water (e.g. pumping from distant rivers or purchasing water from foreign countries for domestic use).

1.2 Desired Technology Improvements

Numerous factors should be considered in an effort to develop more cost-effective desalination methods and leading to the construction of more desalination plants outside of the Mediterranean and Mideast regions. First, energy typically accounts for more than half of a desalination plant's operational costs. Energy to operate an RO desalination system, for example, ranges from 3 – 6 KWh/m^3. Reducing energy use will allow desalination costs to be comparable to conventional treatment means of supplying fresh water, especially in areas where water must be pumped long distances.

Second, process simplification can reduce cost and space requirements. Extensive pretreatment, including chemical dosage systems, can make the desalination process quite complex. The use of energy recovery devices to reduce pumping energy can further complicate the desalination process. Third, alternatives to distillation-based and RO-based desalination processes that do not require the use of pipes and valves made of low carbon stainless steel and other exotic metals for corrosion resistance and/or high pressure conditions will reduce costs. The capital and maintenance costs of both processes can be very significant.

Fourth, a low-pressure desalination process will lessen operational costs. Reverse osmosis requires the use of high-pressure pumps to push water through RO membranes. These high-pressure pumps are normally made of stainless steel or Hastelloy, are very expensive, noisy, cause high vibration, and can create safety concerns within a desalination plant. Plant safety, though not typically highlighted, can be a major concern where operating pressures can reach 1000 psi (82 bar). Numerous catastrophic incidents involving high pressure and/or corrosion have occurred through the years even with continuous improvements in materials and equipment [1].

Fifth, considerable opposition has erupted against brine disposal on land or in oceans due to adverse effects on the environment and to marine life. Technologies need to be developed and deployed to minimize the effect of brine disposal. Finally, alternative energy sources including solar, wind, wave, waste heat, and geothermal energy should be applied where applicable to minimize energy use for desalination.

1.3 Recent Advances

RO membranes continue to improve in efficiency, and this fact, coupled with new energy recovery devices, have already reduced the energy requirement of RO desalination. Further advances are expected in coming years. Several desalination technologies are being developed worldwide that focus on some or all of the issues stated above. Membrane distillation is a thermally driven process that uses hydrophobic membrane to support a vapor-liquid interface. Temperature difference across the membrane causes partial vapor pressure differential, resulting in water evaporating and crossing the membrane and condensing on the cold side. This process requires waste heat in order to be economically viable. Since this is low pressure process, it solves some of the issues discussed above.

Forward Osmosis utilizes a “Draw” solution to create high osmotic pressure across a membrane similar to an RO membrane. This low-pressure process requires waste heat to evaporate the “Draw” solution from water to be economically viable. The technology of dual stage Nanofiltration uses energy recovery devices similar to the RO systems for desalination. Tests conducted indicate that this is a lower energy cost alternative. Nanofiltration is a lower pressure process compared to RO, but still is in need of high pressure components.

Capacitive deionization is a batch process that uses oppositely charged porous electrodes that attract positive and negative ions to the electrodes. Reversal of charge releases ions for disposal. This low-pressure process overcomes many of the factors of concern mentioned earlier. Other technologies such as nano-particles could be used to desalt seawater. Currently, several companies are in the early stages of developing this technology. Several research and development activities addressing brine disposal are also underway to find a means to process reject water for reuse and to use the resulting solid salt component for a variety of applications.

The electrochemical processes of electrodialysis and electrodialysis reversal continue to be used mainly for desalination of brackish water; however, no significant improvement in membranes, modules, and the process has occurred in the last 25 years. A fresh analysis, however, of all components and improvements in the electrodialysis process, including the use of electrodeionization, indicates that such a combination could provide a low energy alternative for sea water desalination. Additionally, the process would be low pressure with relatively high recovery. Plastic pipes, valves and pumps could eliminate many of the issues currently faced with distillation and RO-based processes.

II SIEMENS SOLUTION

2.1 Project Background

In August, 2007, the Singapore Government offered a Challenge Request-For-Proposals (RFP) to industry/institutions to seek ideas for innovative technology to producing World Health Organization (WHO) quality water from seawater at an energy consumption of 1.5 KWh/m3 or less. In this proposal, the Singapore Government offered to share development costs with the winning entry. In October 2007, the Siemens Water Technologies R&D organization submitted a proposal based on an innovative technology. Siemens was announced the sole winner of the contest in June, 2008 from 35 proposal submissions. The project officially began in October, 2008.

The Siemens Project, occurring over a three-year period, shall culminate with a 50 m^3/day demonstration unit built in Singapore. Research is expected to result in breakthrough advances in materials and processes that can be applied to other separation applications and shall be followed by a commercialization phase.

Siemens has proposed to investigate a process utilizing a combination of Electrodialysis (ED) and Continuous Electrodeionization (CEDI). This system is intended to combine proven and novel technologies in unique configurations, with each technology utilized under optimum conditions to minimize overall energy consumption. By taking advantage of synergies between the different technologies, it is believed that the limitations of the current ED and CEDI technologies can be overcome.

2.2 Technology Background

2.2.1 Electrodialysis (ED)

An Electrodialysis module is an example of a complex electrolysis cell where a voltage is applied across an electrode pair (at times there are multiple pairs) to produce the corresponding oxidation/reduction reactions of the electrolytes in the electrode compartments. In an ED module, the current is carried across the module by the transport of ions through ion permeable membranes (ion exchange membranes). An example of the ED process is displayed in Figure 1. The ion exchange membranes are arranged so that there are alternating diluting (product) cells and concentrating (reject) cells that form what are called “cell pairs”. The arrangement of the ion exchange membranes is such that cations (positive ions) transport through a cation exchange membrane (CM) in the direction of the cathode from the diluting cell into the concentrating cell. The cation’s transport is blocked in the concentrating cell by an anion exchange membrane (AM). The anions transfer in the same manner as the cations, but through anion exchange membrane. For the treatment of conductive solutions (seawater, brackish water, etc.), ED provides an efficient means of desalination [2].

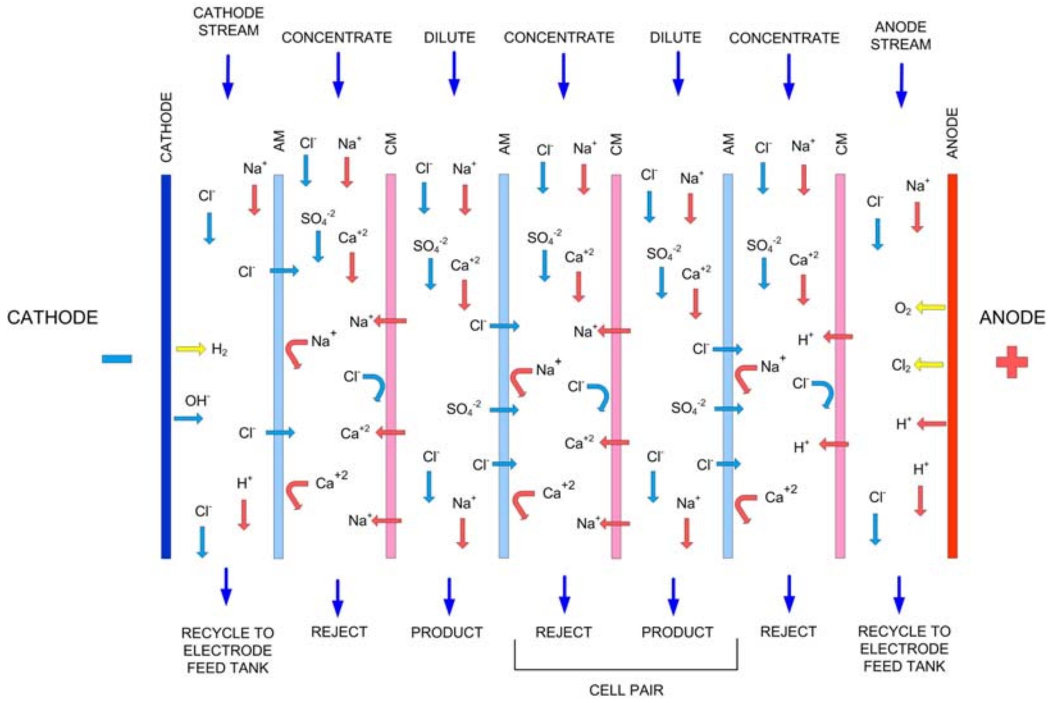

Figure 1: Electrodialysis (ED) Cell Displaying Ion Transport

2.2.2 Continuous Electrodeionization (CEDI)

For less conductive solutions (fresh water, RO permeate, etc.), Continuous Electrodeionization is a highly efficient method of purification. CEDI works in much the same way as ED; however, the diluting cells (and in some cases, the concentrating cells) are filled with ion exchange resin. Figure 2 displays an example of resin filled cells and method of ionic transport. The ion exchange resin provides an ion conductive path to facilitate ion transfer, thus reducing the electrical resistance of the cell. In applications where the feed water is relatively dilute (freshwater, RO permeate), ion exchange resin in the diluting cell will permit the efficient, continuous transfer of ions from diluting cells to concentrating cells. In ultrapure water applications, the ion exchange resin provides the catalytic effect necessary for efficient water splitting (electrolysis of water) which facilitates the transfer of weakly ionized species such as boron, silica, and carbon dioxide [3].

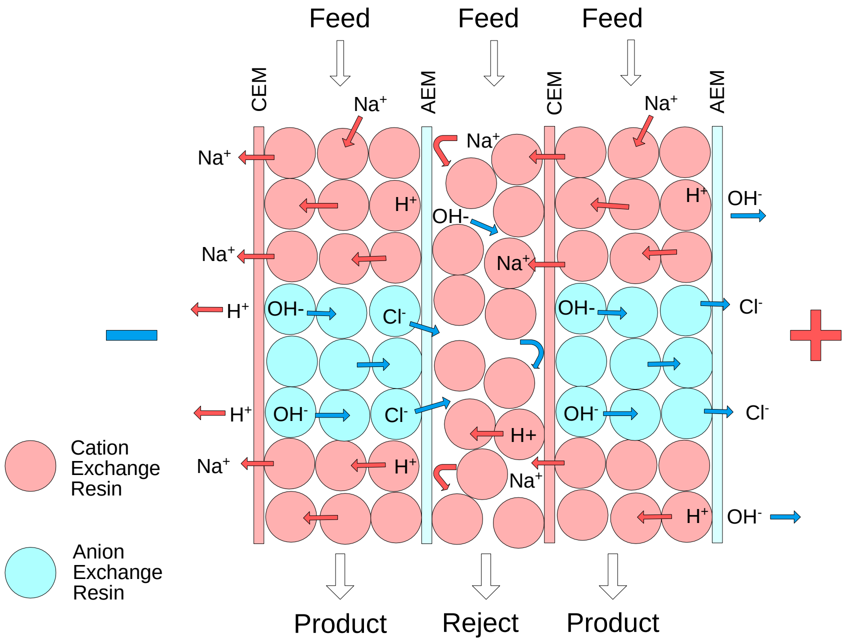

Figure 2: Continuous Electrodeionization (CEDI) Cell Displaying Ion Transport

2.3 Project Update

2.3.1 Initial Testing

During the first year of the project, Siemens focused research on the initial process and membrane characterization. Process studies included intensive investigations into ED and CEDI process characteristics and trends. Standardized test methods were developed for membrane properties and have been used to evaluate membrane samples from around the globe. The suppliers include established companies in Japan, Europe and the USA, as well as emerging suppliers from around the world including China. Key properties important to performance include electrical resistance, transport number, temperature stability, water permeability, and chlorine tolerance. Figure 3 displays the distribution of many of the membranes tested with regard to electrical resistance and membrane permselectivity. As observed in the graph, several membranes approach Siemens' target electrical resistance and several membranes approach the target transport number, but there are few candidates that approach both.

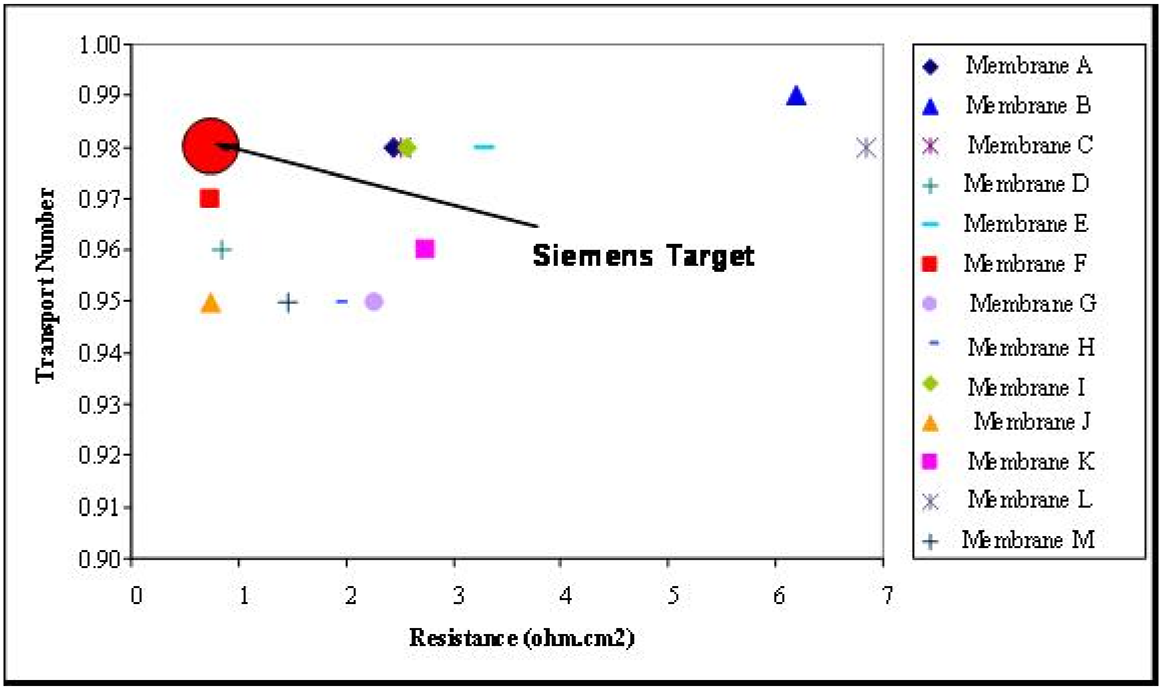

Figure 3: Ion Exchange Membrane Characterization

Initial process characterization testing involved a fresh approach to the study of a variety of parameters including the effect of key membrane parameters, screen design and orientation, the effect of specific ions, temperature, etc. Most prior research has focused on approaching current limit to maximize current density and minimize membrane area and capital cost. For example, there has been extensive work on the effect of screens in ED compartments on mass transfer under turbulent conditions, using both experimental techniques and CFD analyses [4], [5]. Siemens is interested however on optimization of screen design and orientation under non turbulent conditions to maximize ion transfer yet minimize energy consumption.

The results of the experiments described briefly above were used to generate a process model that could then be used to guide the team’s experimental approach as well as serve as an additional design tool. For example, Figure 4 shows the energy consumption for desalting a 35000 ppm NaCl solution using two different sets of currently available ion exchange membranes. Note the approximately 1.3 kWh/m^3 difference in energy consumption as the ED product TDS approaches 2000 ppm.

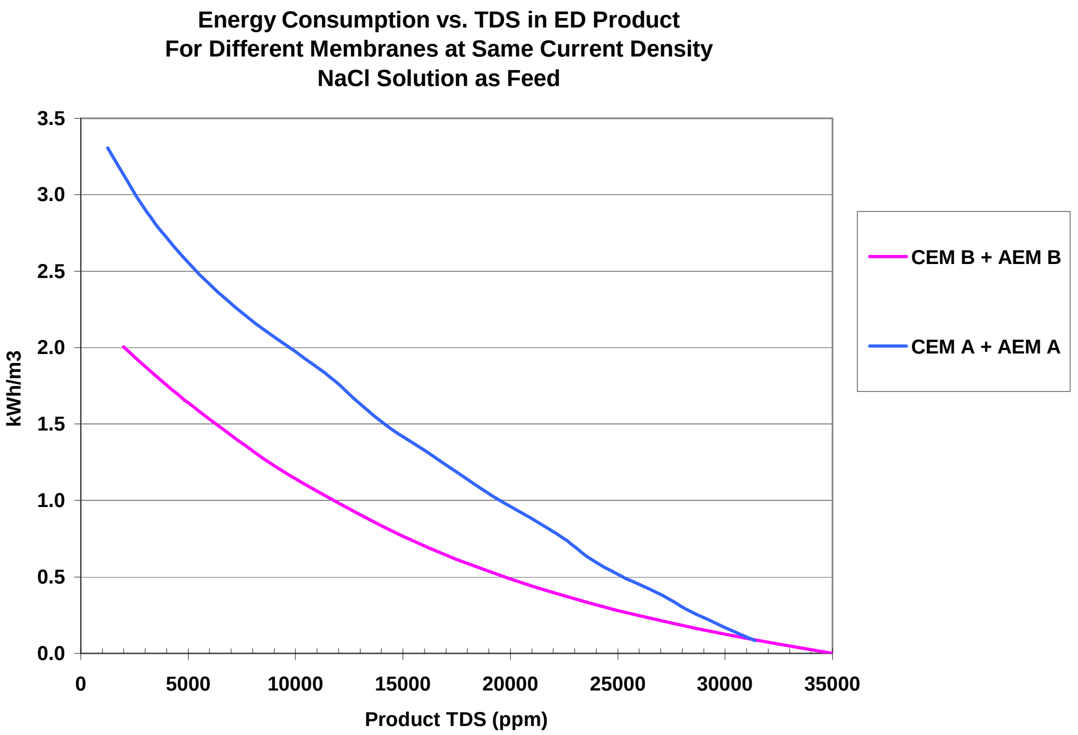

Figure 4: Cumulative Energy Consumption vs Product TDS

2.3.2 Prototype Testing

The developed process model combined with other tools, such as computational flow design and FEA, were used to design an intermediate ED module to observe process characteristics on a larger scale. In the second year of the project, design of this "prototype" was fully underway with the focus transitioning from process testing to mechanical testing. The key challenge of this phase of the project was to design a spacer that was extremely thin (~0.5 mm), yet minimized pressure drop, external leaking, and internal leaking between streams (also known as cross leaking) as each represents a source of significant energy penalty.

Ultimately, creative advances in port design and an intensive investigation into materials of construction contributed to the successful design of the prototype spacers. Figure 5 displays the designs for the prototype spacers. The use of "caps" and "recesses" provided the support to the membrane that minimized the cross leak between the dilute stream and concentrate stream. The investigation into spacer components yield materials that could be formed to 0.5 mm with a very tight tolerance and minimal pressure drop.

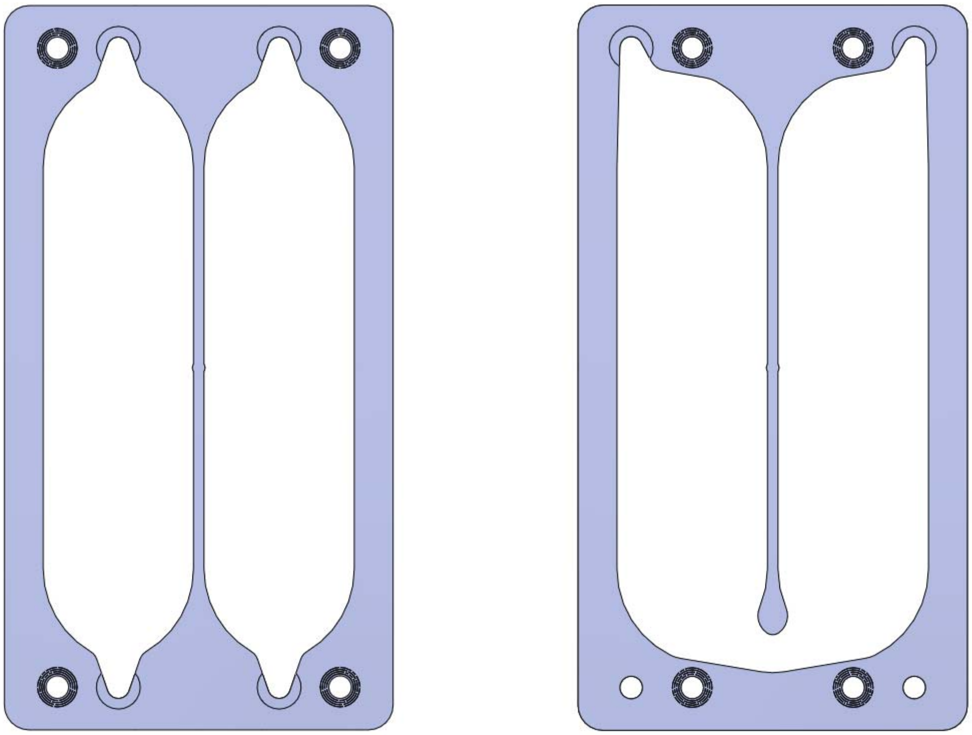

Figure 5: Prototype Spacer Design (Dilute and Concentrate Cells Respectively)

The final prototype modules were tested first with NaCl, then with synthetic seawater, and finally actual seawater. On synthetic seawater, a full desalination run was completed in a single pass. The deionization energy for this test amounted to approximately 1.7 kWh/m^3, though this value did not include pumping energy and power supply efficiency. The test with actual seawater was carried out for several months with no observed change in module performance (stable electrical resistance, current efficiency).

2.3.3 Demonstration Unit

The results from the prototype testing phase were then used, in combination with the process model, to design the ED modules for the demonstration unit. With the success of the prototype design concept, many features remained the same. Using the developed process model, the demonstration system was designed to be three stages of ED followed by one CEDI stage. The flow diagram for the system is shown in Figure 6. Due to the short development schedule, commercially available membranes with electrical resistance 5X that of Siemens's stated target were used in all four stages of the system.

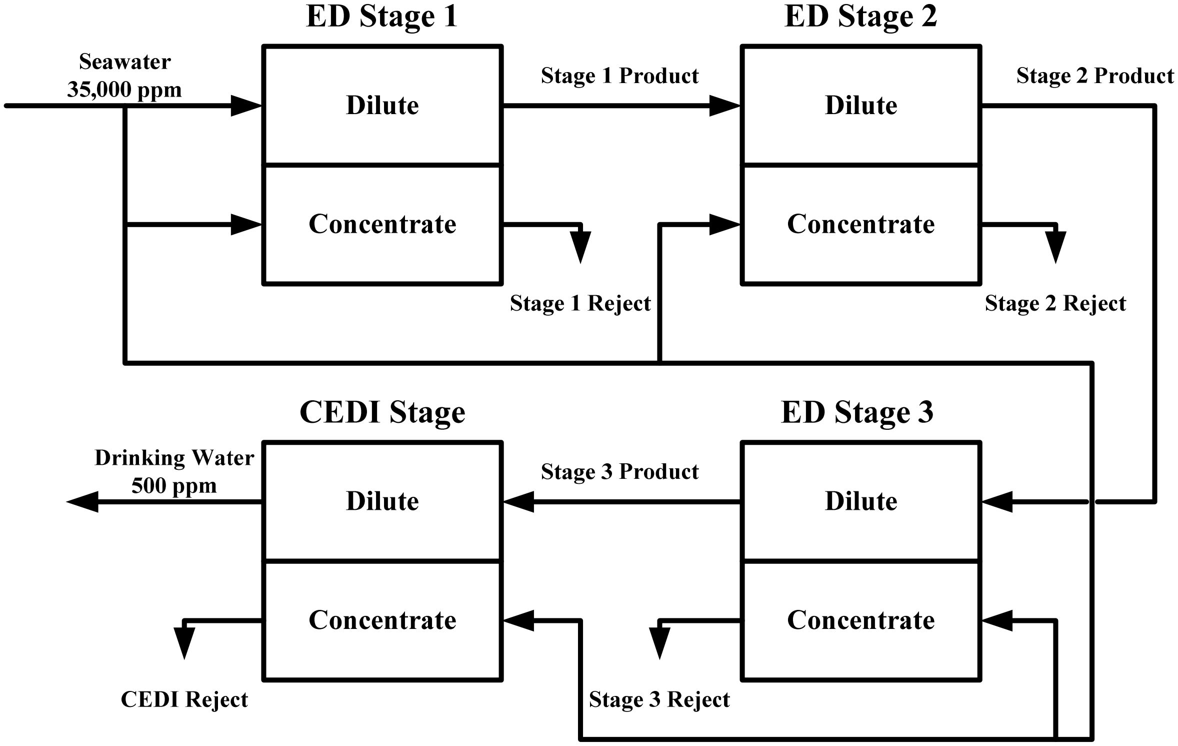

Figure 6: Demonstration System Flow Diagram

Operation of the demonstration unit was commenced December of 2010 and, after some initial debugging, stable operation was achieved shortly thereafter. The average power consumption for duration of the testing was 1.81 kWh/m^3 (displayed in Figure 7). This value was obtained at a recovery rate of approximately 30% and includes the energy required for pretreatment, pumping, and desalting (including power supply efficiency). The average feed water conductivity was 43.5 mS/cm which amounts to approximately 32,000 ppm TDS. The average product water was 0.96 mS/cm or about 500 ppm TDS (displayed in Figure 8). Table 1 displays the analysis for both the feed seawater and the system product water.

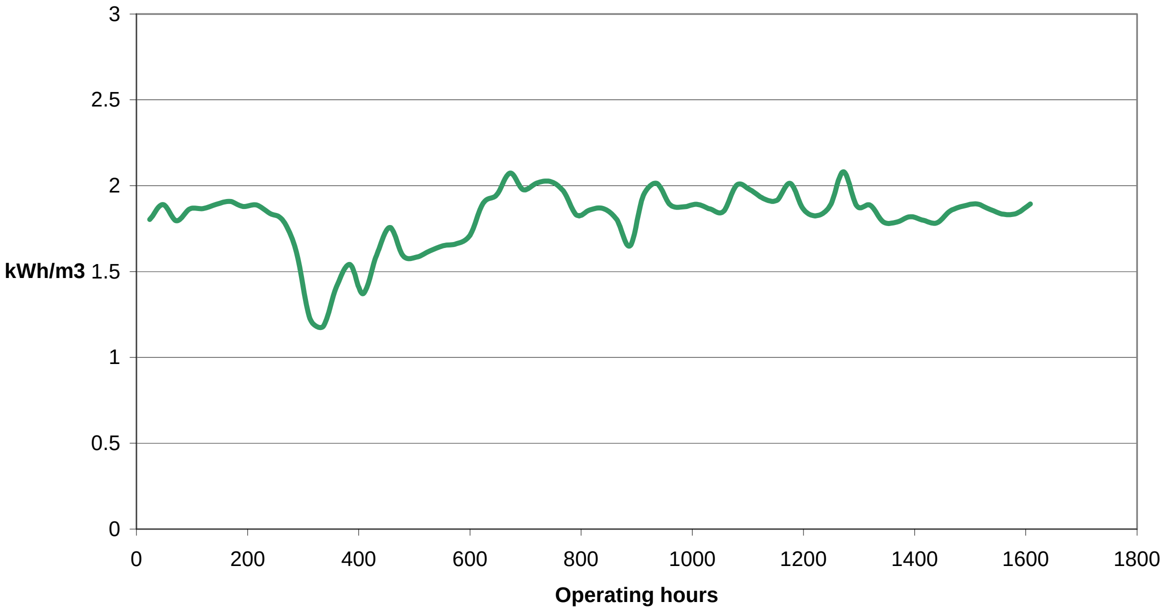

Figure 7: Total Power Consumption

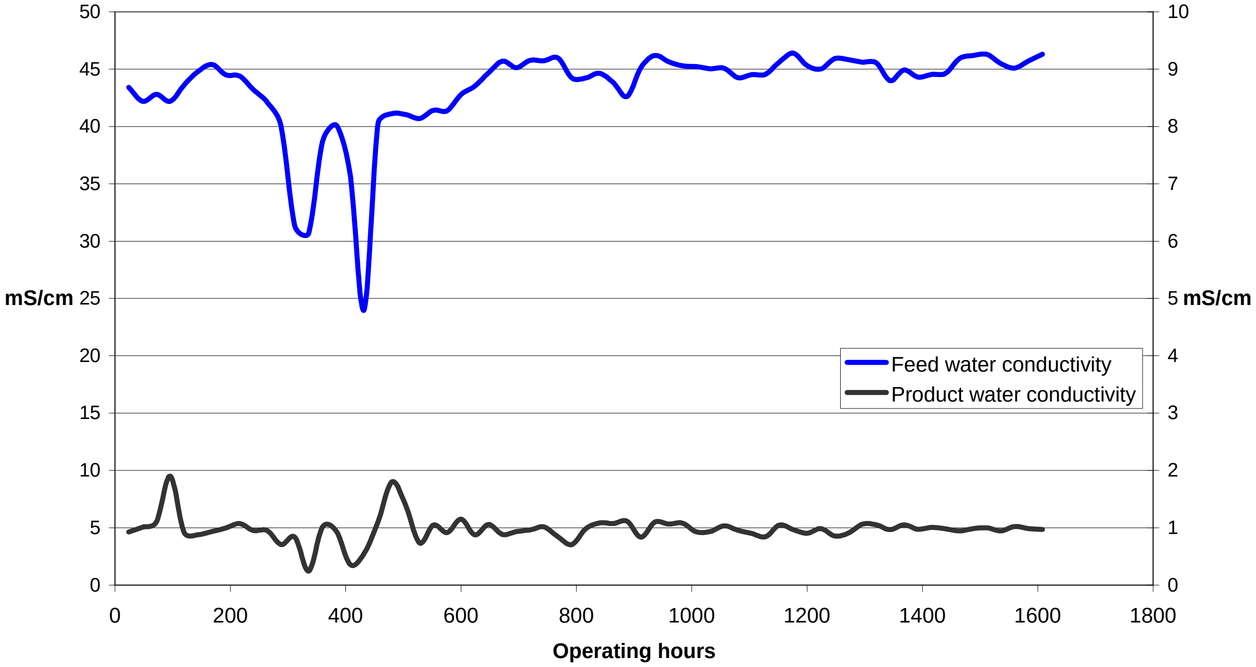

Figure 8: Feed Seawater Conductivity and Product Water Conductivity

Parameter	WHO Drinking Water Guideline	Seawater feed at VSP (Average)	Product water quality (Average)
Conductivity (mS/cm)	-	43.51	0.96
TDS (ppm)	< 600	32,000	475
Chloride (ppm)	< 250	15,958	296
Sulfate (ppm)	< 250	2,200	Non detectable
Boron (ppm)	< 0.5 or 2.4	2.92	0.01
Aluminum (ppm)	< 0.2	2.40	0.16
Copper (ppm)	< 2	2.31	0.22
Iron (ppm)	< 0.3	2.31	0.20
Manganese (ppm)	< 0.4	2.19	0.18
Fluoride (ppm)	< 1.5	1.68	0.27
Sodium (ppm)	-	8,675	182
Calcium (ppm)	-	363	2.28
Potassium (ppm)	-	326	4.65
Magnesium (ppm)	-	1,095	1.02
E. Coli (cfu/100ml)	< 1	< 1	< 1

Table 1: Feed Seawater and Product Water Analysis

Although significant reductions in energy consumption were realized, the target of 1.5 kWh/m^3 was not achieved. There are several factors that have contributed to this result, including the relatively high resistance of the membrane as well as several module design limitations. The key module design limitation appears to be controlling the crossleak from the dilute compartment to the concentrate compartment. Controlling this crossleak is made challenging by the drive to decrease cell thickness while minimizing the pressure drop in the module. It is believed that further advancement in the design of the ED module as well reduced electrical resistance of the ion exchange membrane will drive the energy consumption closer to the original target.

One of the most encouraging aspects of the results is the observed operational stability. After greater than two months of operation and the occasional upset, the performance of the system appears responsive and robust. Testing of the system will continue and the results will contribute to the commercialization efforts that are currently underway.

2.3.4 Commercialization Effort

In parallel with the project's demonstration effort, Siemens has also been evaluating the path to commercialization. The objective of this phase of the project is to develop a technology that offers the customer the lowest total cost of ownership. This may not mean the lowest energy process but, depending on the specific application, likely a balance between energy (operating) cost and capital investment. An example of this balance is displayed in Figure 7. To strike this balance, major developments in the components of ED modules are required. Specifically, high performance/low cost ion exchange membrane and low cost/highly automated ED modules are the major development focal points of the commercialization phase for this project.

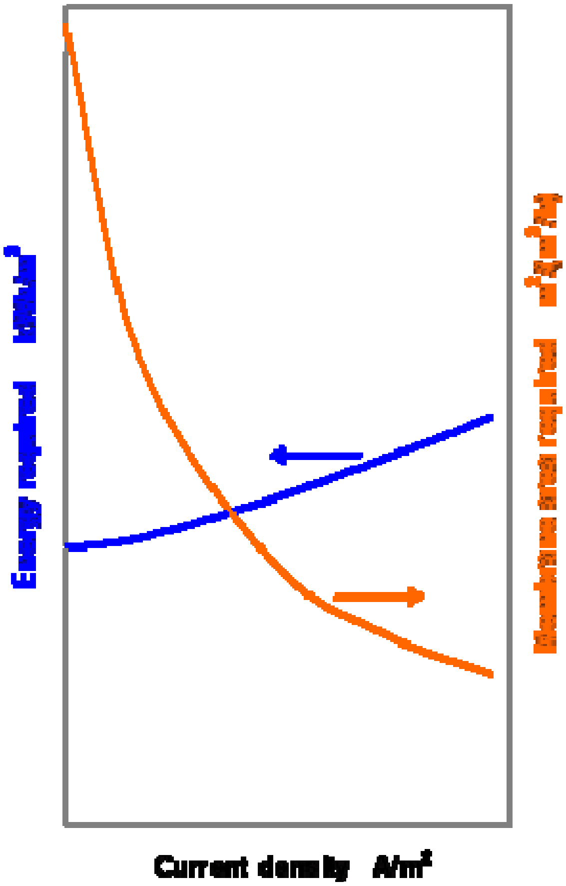

Figure 9: Demonstration System Flow Diagram

Ion exchange membrane represents the cornerstone of the successful development of a low cost seawater desalination product. To establish a competitive electrochemical solution, the membrane target shown in Figure 3 must be approached. In addition to approaching this target, the cost of such a membrane must be dramatically reduced from that which is currently available. Siemens has been evaluating both commercially available membranes and custom membranes from various membrane suppliers around the world.

Recently, several promising candidates have emerged. These candidates have approached the established electrochemical targets and appear to be within reach of Siemens' low cost target. Pilot testing of these candidates is currently underway and will continue through the calendar year. Figure 10 displays the electrochemical properties of these prototype membranes with respect to Siemens' target and the membrane that was used in the demonstration system.

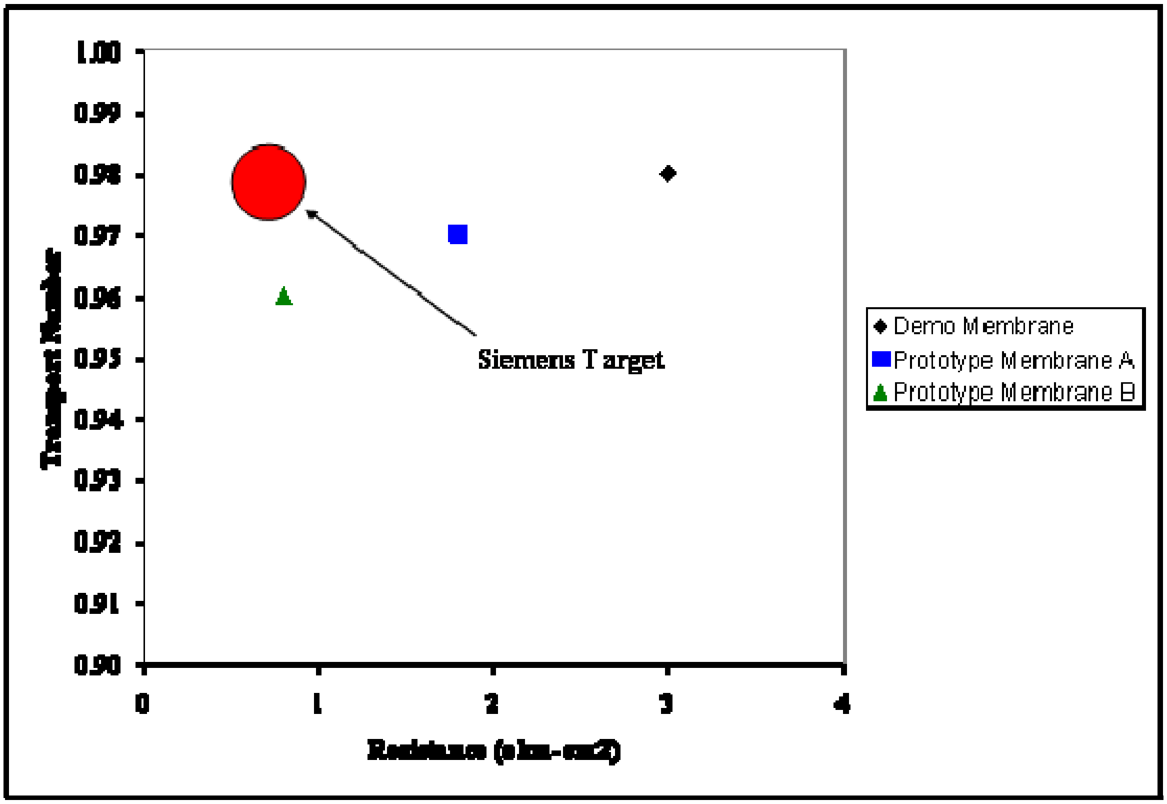

Figure 10: Promising Membrane Candidates

Advances in the design of the module are critical to the commercialization effort as well. In addition to addressing the challenges described above (pressure drop, cross leaking, etc.), a competitive ED/CEDI platform must be extremely low-cost. To achieve this, not only do the components of the module need to be low cost, the production process must be designed for ease of assembly. To this end, Siemens has investigated many design concepts and there appear to be several options available. Prototype designs of several of the most promising options are currently being developed and testing will take place during the next year of the project.

III CONCLUSIONS

Thus far, the testing results of this project have shown that a significant reduction in energy is achievable when desalting seawater with Siemens' ED/CEDI solution. Advancements in module design and process optimization have contributed to this achievement, even with the use of commercially available membranes with high relative resistance. Efforts toward the development of high performance, low cost ion exchange membranes and further advancements in module construction are now the focal points of Siemens' desalination project. The objective is to provide the lowest total cost of ownership to the customer.

Acknowledgments

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